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GUGGENHEIM AERONAUTICAL LABORATORY

CALIFORNIA INSTITUTE OF TECHNOLOGY

AN APPARATUS FOR THE STUDY OF THE TURBULENT DIFFUSION FLAME

Thesis
by
Lt.Comdr. Leo W. Mullane, USN

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Thesis

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Lt. Comdr. Leo W. Mullane, USN

In Partial Fulfillment of
The Requirements for
Professional Degree of
Aeronautical Engineer

California Institute of Technology
Pasadena, California

1947

PREFACE

It is with deepest gratitude that I acknowledge the help and encouragement of Prof. B. H. Sage and Dr. E. W. Hough.

Without their assistance the work on this thesis could not have been completed.

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SUMMARY

The project to study the turbulent diffusion flame[1], by the Department of Chemical Engineering of the California Institute of Technology, is quite comprehensive. Only a small portion of the project was included in the scope of this thesis.

A study will be made of the turbulent diffusion flame that is formed when fuel gas is introduced, through the end of a 1-inch-diameter tube, into air, flowing in a 4-inch-diameter tube, and combustion is started. The plan of investigation is divided into two parts. First, a study will be made of the mixing zone[2] when combustion is not occurring; and secondly, a study will be made of the combustion zone when combustion is taking place.

The work accomplished in the scope of this thesis was the design and assistance in the fabrication and assembly of the equipment necessary to conduct this investigation. This was completed with the exception of the sampler to be used in obtaining samples of the burning gases. In addition, one series of tests was made at one stream velocity.

The equipment functioned very well during the series of runs. Recommendations for a few minor changes are included in this report. The incorporation of these changes should increase slightly both the speed of taking data and the accuracy of the results.

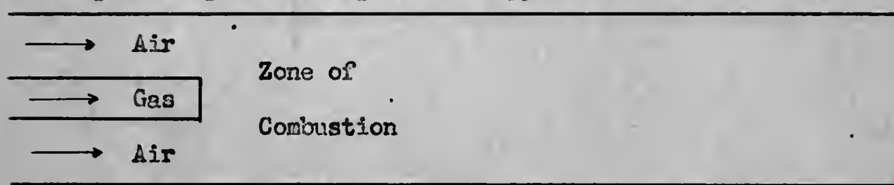
The results obtained in the series of tests indicated that the desired data can be obtained with this equipment.

(1) Turbulent diffusion flame - a flame formed in the mixing zone of two gases diffusing into each other.

(2) Mixing Zone - that section inside of the combustion tube downstream from the end of the gas inlet tube.

STATEMENT OF THE PROBLEM

A study will be made, by the Department of Chemical Engineering of the California Institute of Technology, of the turbulent diffusion flame that is formed when fuel gas is introduced, through a 1-inch-diameter tube, into air, flowing in a 4-inch-diameter tube, and combustion is started. A schematic drawing showing the Arrangement of Apparatus is shown below:



The two main objectives of this project are: the determination of the characteristics of the zone of combustion; and the correlation of the results obtained from a study of the mixing zone when combustion is not occurring with those obtained when combustion is taking place. It is believed that the results will be analogous to those found by Burke and Schumann[1] for the molecular diffusion case.

The method of investigation of the problem will be as follows:

First the diffusion, under turbulent flow conditions, of fuel gas and air without combustion occurring will be studied. The air and fuel gas will be introduced into the combustion tube at the same temperature and average velocity. An attempt will be made to vary the turbulence. Concentration of fuel gas, pitot tube pressure, and thermocouple electromotive force measurements will be made at various locations along the longitudinal axis of the combustion tube. At each of these locations, measurements will be made on a

(1) Burke & Schumann - (Diffusion Flames) - Ind. Eng. Chem., 20, 998 (1928)

traverse along a diameter of the 4-inch-diameter combustion tube. The equipment should be capable of making the traverse measurements at 0.050 inch intervals in regions where the rate of change of concentration is high enough to warrant it. Velocity and turbulence will be varied through predetermined ranges.

Next, a study of the diffusion of fuel gas and air with combustion occurring will be made. In general, the procedure will be the same as for the previous study with an attempt being made to duplicate the conditions insofar as possible, that were obtained in the runs without combustion.

The work accomplished on the project, that is included in the scope of this thesis, was to design and assist in the fabrication and assembly of the equipment necessary to conduct the pre-combustion phase, and to make one series of runs.

DISCUSSION AND DESCRIPTION OF THE EQUIPMENT

It was originally planned to include in this project several sizes of combustion tubes and several different gaseous fuels. When it was decided that copper or stainless steel tubing would be required for the combustion tube, the scarcity of these materials made it necessary to limit the project, for the present, to the one combustion tube of 4-inch-diameter, extra strong, copper pipe. Also the cost of using gaseous fuels other than fuel gas was found to be prohibitive for a complet investigation. At a later date when more is known about the subject, it may be feasible to use other gaseous fuels for specific tests.

The design, fabrication and assembly of the equipment for this project is complete with the exception of the sampler to be used in the combustion zone while combustion is occurring. It has tentatively been decided to use the isentropic cooling type for this purpose. Mr. Gilmore of the Department of Chemical Engineering, California Institute of Technology has completed the design of a sampler of this type.

A description of the rest of the equipment is given below:

Schematic drawings of the apparatus are shown in Figures 1 and 2. A view of the entire test section is shown in detail A of Figure 1. The combustion tube assembly is shown in detail B of Figure 1. The combustion tube, part A, of detail B is made of 4-inch, extra strong, copper pipe.

The cooling jacket, part B is 6-inch standard brass pipe which is sealed to the combustion tube with expansion seals, part C. The jacket is provided with $\frac{1}{2}$-inch brass pipe cooling water entrance and exit lines (not shown). There are eleven sampling ports located along the longitudinal axis of the combustion tube, as shown on detail A of Figure 1. The construction details of one of these ports are shown as part D on detail B of Figure 1. The sampling tube, part E, is made of two concentric metal tubes and is similar to a pitot tube. The outside tube is made of standard brass tubing with an outside diameter of 1/8 inch. The inside tube is made of stainless steel tubing with an inside diameter of 0.03125 inch and an outside diameter of o.0625 inch. The samples will be drawn in through the stainless steel tube. The annular space between the brass and steel tubes serves as the static pressure chamber when the sampler is used as a pitot tube. In addition, thermocouple leads (not shown) are run in this space to the top of the bend in the tube. They will be used to determine an apparent temperature of the air stream. The bottom of the sampling tube rests on an inverted vernier height measuring gauge. The location of the sampling tube inlet above or below the centerline of the combustion tube can be measured to an accuracy of 1/500 of an inch. A piezometer will be located near each end of the combustion tube to obtain the average static pressure at these points. Thermocouples will be located in the combustion tube wall at each of the five points which are spaced 12, 18, 24, 48, and 84 inches from the upstream end of the combustion tube. The combustion will be started by a spark plug (not shown) inserted in one of the sampling ports. The fuel is introduced to the air stream from a 1-inch-diameter, copper pipe, part G, Figure 1. The outside surface of this pipe has been conically tapered and polished. The diameters of the combustion tube and gas inlet tube were chosen so as to provide nearly a stoichometric mixture for combustion at the same average velocity of flow. The area ration of the two pipes is 12:1.

The air induction system, made up of ducts A through Q in Figure 2, delivers meted air to the combustion tube at a predetermined temperature, within 0.1° F. The air velocity can be varied, by means of a variable speed blower, so as to provide a Reynolds number range of from 25,000 to 300,000. The air is taken from the outside atmosphere at duct A where it is filtered and heated. The blower is located at G. Additional heat can be added at duct H by the automatic air temperature control. The rate of air flow can be measured by the Venturi meter, I. Turning vanes are provided in duct N and a honeycomb section in duct O. The air enters the combustion tube, part R, Figure 2, after passing through the contraction sections P and Q.

A burner (not shown) to burn the air-gas mixture during the runs that are made without combustion, is located at the end of the combustion tube. The burner is made of standard 8 inch diameter steel pipe 12 inches long. Two hundred copper tubes 1/4 inch in diameter are located longitudinally in the steel pipe. The copper tubes are held in place by soldering to two end plates, of 3/8 inch brass plate, that have been drilled to allow the copper tubes to pass through.

The combustible gases pass through the inside of the copper tubes and are ignited at the outside surface of the downstream end plate by means of a pilot light (not shown). The tubes and end plate are cooled by water, which is circulated inside of the steel pipe and end plates and outside of the copper tubes.

The samples obtained were analyzed by a gas density method. The pressure measurements were made by means of water-in-glass manometer and by a mercury-in-glas barometer. A White potentiometer will be used for the measurements of the thermocouple electromotive forces.

The entire test section was built to close tolerances so that accurate results might be obtained. Since it was anticipated that the location, relative to the test section, of the critical region in the mixing zone would vary for different average stream velocities; provisions for accurate measurements were made along the major portion of the test section. The sampling ports were located along the longitudinal axis of the combustion tube to an accuracy of ± .003 inches of the horizontal centerline of the combustion tube, and the angular displacement in any direction from the vertical diameter of the combustion tube did not exceed ± 30 minutes. The upper surface of the sampler sleeve and the sampling port plugs fit within ± .001 inches of the inside surface of the combustion tube.

TEST RESULTS OBTAINED

A. Discussion

In the short time that was available after the equipment was completed, it was decided to make one series of test at one stream velocity in an attempt to ascertain the capabilities of the equipment and to locate any inherent weaknesses in the design.

Four samples were taken at each of five sampling ports. The ports where samples were taken are labeled Stations 1, 2, 3, 4, 5, and are 3, 7, 17, 35, and 71 inches respectively from the end of the fuel inlet pipe.

At each of the five stations, four samples were taken along a radius from the center of the combustion tube downward. The four samples were labeled A, B, C and D and were taken along the described radius, at $\frac{1}{2}$-inch intervals, from the centerline of the combustion tube. Sample A being taken at the centerline and Samples B, C and D being taken at a radius of $\frac{1}{2}$, 1, $1\frac{1}{2}$ inches respectively.

The average velocities of the inlet air and the fuel gas were adjusted so that the velocity of the fuel gas, at a point 0.25 inches from the inside of the 1-inch-diameter fuel feed line, was equal to the velocity of the air, at a point 0.25 inches from the outside of the 1-inch-diameter fuel feed line. Both measurements were made one inch upstream from the point of mixing and were determined by pitot tube readings. The average velocities were held constant for the rest of the runs.

It had originally been intended to maintain the two flows at 100.0 ± 0.2°F but due to the failure of the inlet air heating circuits just prior to starting the runs, the temperature of the gases were held at 88.0 $\pm$ 2.0°F by manually controlled heating.

B. Procedure

The procedure followed in making a determination is outlined below:

1. The sampler was put in the proper sampling port and the sampling head was elevated to the top of the combustion tube. The reading on the vernier height measuring gauge was then made. The sampling head was then lowered to the center of the combustion tube. To do this accurately the pointer on the vernier height measuring gauge was lowered by an amount equal to the known radius of the combustion tube less the known radius of the pitot tube. The sampler was then in position for Sample A.

2. The sampling head was then rotated until the maximum velocity head reading was obtained on the manometer. This located the position of the head directly upstream. The pitot tube reading was then taken. This procedure was not entirely satisfactory. For recommended improvement see page 15.

3. A sample bulb, which had previously been evacuated to an absolute pressure of 1.5 millimeters of mercury, was then attached to a sampling tube. The sampling tube was connected to the inside tube of the sampler. By means of a stop cock, the flow into the sampling bulb was regulated so that the pitot tube manometer reading was zero. This insured that the sample was being withdrawn at nearly the same velocity as the flow at the point of sampling.

The sample velocity was less than the velocity of the stream at the point of sampling by an amount equal to the pressure drop in the line from the pitot opening to the manometer. This pressure drop was considered to be very small since the smallest restriction was at the opening into the stream.

After the stop cock had been turned fully open, the sample bulb was left connected until the original pitot tube reading was noted. This method gave a definite, stable pressure at which the sample was known to have been taken and could then be corrected to standard conditions very easily.

4. A thermometer located near the sampling bulb during the sampling period was read to give the temperature of the gas collected.

5. The sampling bulb was then weighed on a balance to an accuracy of 1 milligram.

6. The sampler was then lowered 0.5 inches by means of the vernier height gauge to position B and the procedure repeated.

C. Data

The data obtained from this series of runs are tabulated in the Appendix, Sections 1 through 3.

D. Calculations

The calculations required in the presentation of the data obtained were very simple. As an example, those for Station 2, Position B, are given below:

1. Weight of Sample.

Tare	26.3804	grams
Bulb and sample	25.6050	grams
Sample	0.7754	grams

2. Correction for Temperature and Pressure changes.

Now: $d_1 = \frac{P_1 T_2}{P_2 T_1} \times d_2$ and since the volume of the sample was constant we may write:

$$W_1 = \frac{P_1 T_2}{P_2 T_1} \times W_2$$

Let W_2 be weight obtained from the sample weighings and W_1 be the sample weight corrected to standard conditions.

$$\therefore W_1 = \frac{760 \times 305.5}{754.9 \times 273} \times 0.7754 = 0.874 \text{ grams}$$

Now the weight of a sample of fuel gas = 0.742 grams and the weight of a sample of air = 0.991 grams at 0° centigrade and 760 millimeters of mercury absolute. The value, of the weight of the fuel gas, checked quite closely with that given by the Southern California Gas Company. Therefore we may calculate the percent fuel gas in the sample by the following equation:

$$\% \text{ Fuel gas} = \frac{0.991 - \text{Wt. of Sample}}{0.991 - 0.742} \times 100$$

$$\% \text{ Fuel gas in 2-B} = \frac{0.991 - 0.874}{0.991 - 0.742} \times 100 = 46.9\%$$

A list of these results is given in the Appendix, Section 4.

3. Calculation of Average stream velocity.

The average stream velocity was computed by taking the average of the velocities of the inlet air and the inlet gas in proportion to their respective areas.

a. Calculation of Average Inlet Gas velocity.

An orifice meter with a square-edged orifice plate of 0.800 inch in diameter was installed in the inlet gas line. The manometer reading across this orifice plate was 2.95 inches of water. Using the formula given in "Fluid Meters"(1) for the calculation of flow by a square-edged orifice we have:

$$q_1 \text{ (c.f.s. at } p_1, t_1) = 0.06068\ KY_1D_2^2 \left(\frac{h_w^{1} T_1}{p_1 G y}\right)^{1/2}$$

where

G = Sp. grav. of gas (air = 1.0) = 0.748

h_w^1 = Diff. press. in inches of water = 2.95

K = Flow Coeff. = 0.7047 at Re. = 75,000 (Table 6)

p_1 = Absol. press. in pounds per sq. in. = 14.45

T_1 = Absol. temp. in °R = 549

y = Super-compressibility factor = 1.0

D_2 = Orifice plate diameter in inches = 0.800

Y_1 = Expansion Factor 0.998 from Fig. 72 - "Fluid Meters"

therefore

$$q_1 = 0.06068 \times 0.7047 \times 0.998 \times 0.64 \left(\frac{2.95 \times 549}{14.45 \times 0.748 \times 1.0}\right)^{1/2}$$

q_1 = 0.336 c.f.s. at 549° R and 746 mm. Hg.

$$q_0 = \frac{746}{760} \times \frac{460}{549} \times 0.336 = 0.276 \text{ c.f.s. at } 460° \text{ R and } 760 \text{ mm. Hg.}$$

therefore

$$\text{Velocity} = \frac{q_0}{\text{Area}} = \frac{0.276}{0.00545} = 50.7 \quad \text{ft./sec.}$$

(1) ASME Research Publ. - (Fluid Meters) - ASME, 4th Ed., 50 (1937)

Reynolds No. check:

$$Re = \frac{DVd}{\mu} = \frac{0.83 \times 50.7 \times 1.56 \times 10^{-3}}{2.07 \times 10^{-7}} = 31,700$$

Now $K = 0.7195$ at $Re = 31,700$ (Table 6)

$\therefore$ Velocity $= \frac{0.7195}{0.7047} \times 50.7 = 51.8$ ft./sec.

b. Calculation of Average Inlet Air Velocity.

A Venturi meter was installed in the inlet air line. The manometer reading across the Venturi was 7.0 inches of water. Using the formulae given in "Fluid Meters", pg. 127, for the calculation of the weight flow of a gas through a Venduri meter we have:

$$W = 0.8596 \frac{C D_2^2}{(1-B^4)} \left[\frac{G p_2}{T_1} (p_1 \; p_2) \right]^{1/2}$$

where

C_D = Coeff. of Discharge

D_2 = Dia. of Venturi throat in inches = 2.404

B = Ratio of throat dia. to pipe dia. = 0.40

G = Spec. gr. of gas (Air = 1.0) = 1.0

p_2 = Absol. Press. at throat in lbs. per sq. in. = 14.20

p_1 = Absol. Press. at Entrance in lbs. per sq. in. = 14.43

T_1 = Absol. Temp. in °R = 549

W = Mass rate of flow in lbs. per sec.

To determine C_D estimate $Re = 100,000$

then

C_D ($B = .5$) = 0.980 from Fig. 63, "Fluid Meters" then

$$C_D\ (B = .4) = \left[\frac{1 - B^4}{(1-B^4) + \left(\frac{0.9375}{C_{D_{B=.5}}^2} - 0.9375\right)}\right]^{1/2}$$

therefore

$$C_D\ (B= .4) = \left[\frac{1 - (.4)^4}{(1-.4^4) + \left(\frac{0.9375}{(.98)^2} - 0.9375\right)}\right]^{1/2}$$

$$C_D\ (B = .4) = 0.982$$

then

$$W = 0.8396 \times \frac{.982 \times 5.76}{(.9865)^{1/2}} \left[\frac{1.00 \times 14.20}{549} \times .23\right]^{1/2}$$

$$W = 0.378 \text{ lbs./sec.}$$

therefore

$$\text{Velocity} = \frac{W}{Ad} = \frac{.378}{.074 \times .0766} = 66.7 \text{ ft./sec.}$$

$$Re = \frac{0.3184 \times 66.7}{1.566 \times 10^{-4}} = 135,600$$

There is no change in C_D between Re = 100,000 and 135,600.

c. Calculation of average stream velocity based on area ratios.

$$\text{Average Velocity} = V_1 \times \frac{A_1}{A_T} + V_2 \times \frac{A_2}{A_T}$$

$$= 51.8 \times \frac{1}{13} + 66.7 \times \frac{12}{13}$$

Average Stream Velocity = 65.5 ft./sec.

4. Calculation of Average Reynolds Number.

Now: $Re = \frac{DV}{Y} = \frac{0.33 \times 65.5}{1.510 \times 10^{-4}} = 143,000$

Where Y = Kinematic Viscosity of gas mixture.

DISCUSSION

A. Functioning of Equipment

The equipment functioned very well during the series of tests that were made; however, due to the elementary nature of these tests, the equipment cannot be considered to have had a thorough "shakedown" test.

It was discovered, quite some time after the tests were completed, that the line leading from the static side of the pitot tube to the manometer was plugged. This indicated that the pitot readings were made with a closed manometer system. Therefore the values obtained from these readings would be valid for comparitive purposes but not in determining the absolute magnitude of the quantities. The tests would have been repeated if sufficient time had been available.

During the running of the tests it became evident that some minor changes in the equipment should be made. These are outlined below:

1. The sampler should be provided with some positive means of locating the sampler head directly upstream. This would eliminate the trouble of locating the sampler head at each position, and would be more accurate than the determination of its location by the pitot tube manometer readings. The slight descrepancies in the pitot tube manometer readings that were obtained in the series of tests are believed to have been caused by the improper location of the sampler head.

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2. A support should be installed near the sampler to carry the weight of the pressure and sampling lines. The sampler tubes are so small that the weight of the lines and fittings

attached to them causes the tubes to deflect appreciably.

3. A more sensitive valve, such as a needle valve, installed in the fuel gas feed line would be quite helpful in adjusting the inlet fuel gas velocity.

4. The bracket that attaches the vernier height measuring gauge to the sampler sleeve should be reworked so that it has the same shape as the sampler sleeve at the point of attachment. This would facilitate the installation and removal of the samples from the sampling ports since the sampler sleeve wrench would fit more easily.

B. Accuracy of Results

The results obtained from the series of tests indicate a precision of about one percent in the percent fuel gas in the sample. The probable error of the absolute value of the percent fuel gas varies from 36 percent at a concentration of 4.4 percent fuel gas to 2 percent at a concentration of 99.1 percent fuel gas. For the present investigation this should be sufficient since the relative compositions are of primary importance. The pitot tube manometer can be read to an accuracy of two millimeters, and since this reading is used only as a correction factor in determining the composition of the sample, this error is negligible.

C. Discussion of Results

The results of the series of tests have been plotted on three graphs, Figures 3, 4 and 5.

Figure 3, which gives the plot of the concentration along the combustion tube at the various positions, is of value only in determining for future investigation, how far downstream from the point of injection the sampling should take place.

Figure 4, gives the plots of the concentrations at a cross-section of the flow for each of the five sampling stations. If it is noted that Position B, which corresponds to a point 0.5 inches from the centerline, is the point where the fuel gas and air flows meet; then it is apparent that the shape of the concentration curve on each side of this point is nearly identical for each individual station.

Using the values for the upper and lower combustion limits of methane, ethane, propane and butane given by Coward and Jones(1) and assuming a fuel gas composition as given below;

Methane	85 percent
Ethane	15 percent

we can calculate the upper and lower combustion limits of the fuel gas by the formula of Le Chatelier as modified by Coward and Jones(1). The equation is as follows:

$$L = \frac{100}{\frac{p_1}{N_1} + \frac{p_2}{N_2} + \frac{p_3}{N_3} + \cdots}$$

in which p_1, p_2, and p_3 ... are the proportions of each combustible gas present in the original mixture, and N_1, N_2, and N_3 ... are the lower limits in air for each combustible gas separately. Now, substituting in the equation for the lower limit, we have;

$$L = \frac{100}{\frac{85}{5.3} + \frac{15}{3.22}} = 4.83\%$$

Also determining the upper limit by an analogous equation, we have:

$$U = \frac{100}{\frac{85}{14.3} + \frac{15}{11.75}} = 13.8\%$$

Now, using the values of the upper and lower combustible limits thus obtained, the zone of combustible gas along the combustion tube is

(1) Coward & Jones - Limits of Inflammability of Gases and Vapors, Bull. 279, U.S. Dept. of Commerce - 1928

shown in Figure 5. This plot is not considered accurate since an insufficient number of samples were taken to accurately determine the shape of the zone of combustible gases.

The calculation of the average stream velocity was based on the average of the pitot tube readings taken at the four positions. The fuel air ratio that is obtained, when equal average stream velocities are maintained in the two feed lines is 1:12.

D. Recommendations for Further Work:

Based on the results obtained, it is believed that a great deal of very interesting data can be obtained with this equipment and the accuracy of results will be satisfactory for a preliminary investigation of this kind.

It would be very interesting to check the shape of the concentration curves of Figure 4 on each side of the point of mixing. This would define more closely the zone of combustible gases show in Figure 5.

The investigation of the effects of the various parameters on on the diffusion of the fuel gas into the air will entail a great deal of work; however, it is possible to get data quite rapidly using the gravimetric determination of the gas concentration. It is sincerely regretted that sufficient time was not available to obtain a more complete set of data for presentation at this time.

FIGURE 9
TURBULENT DIFFUSION
FLAME APPARATUS

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INLET END COMBUSTION TUBE SECTION T.D.-FLAME

25420

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LAB - LAYOUT

25402-A

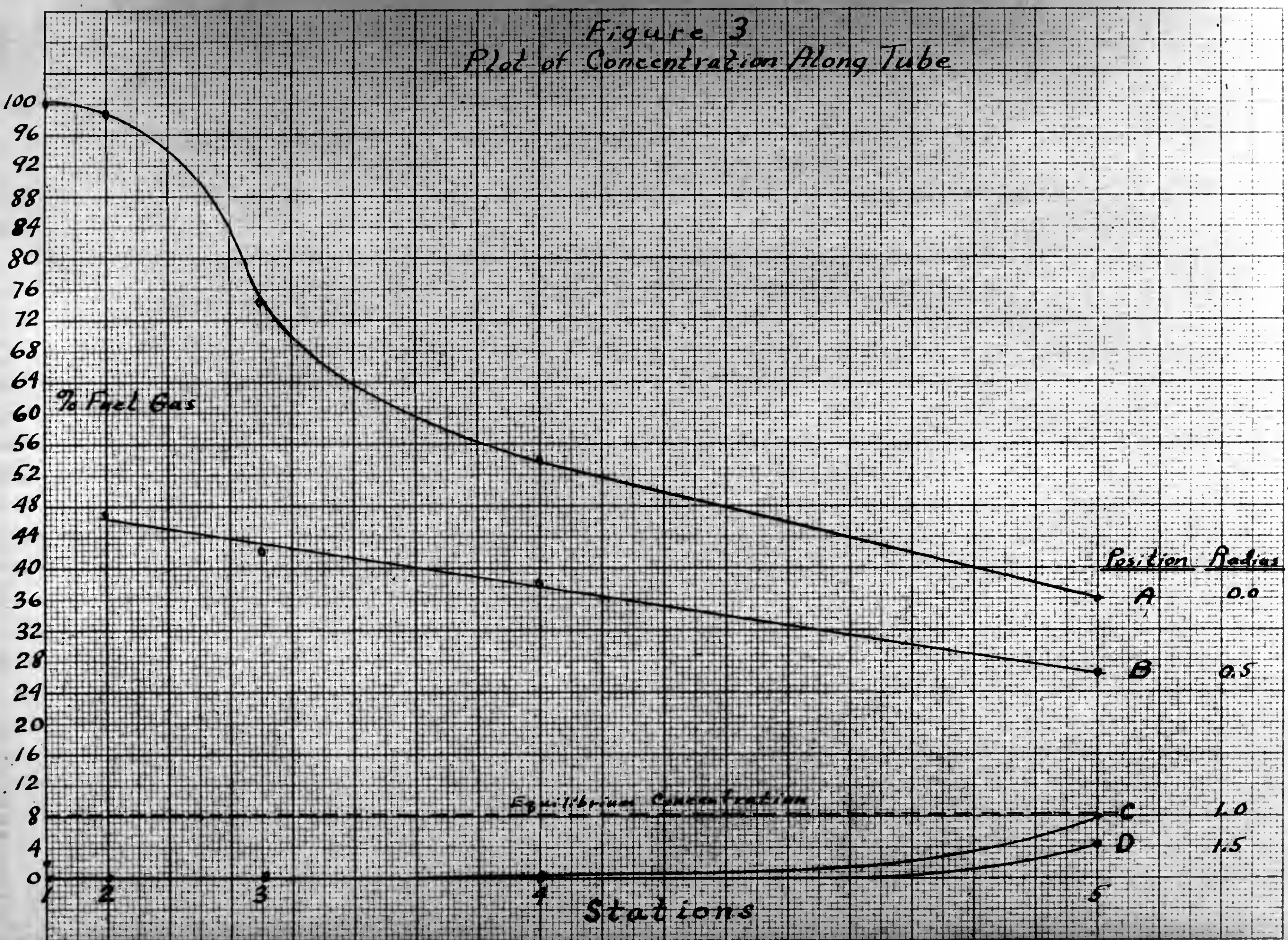

Figure 3
Plot of Concentration Along Tube

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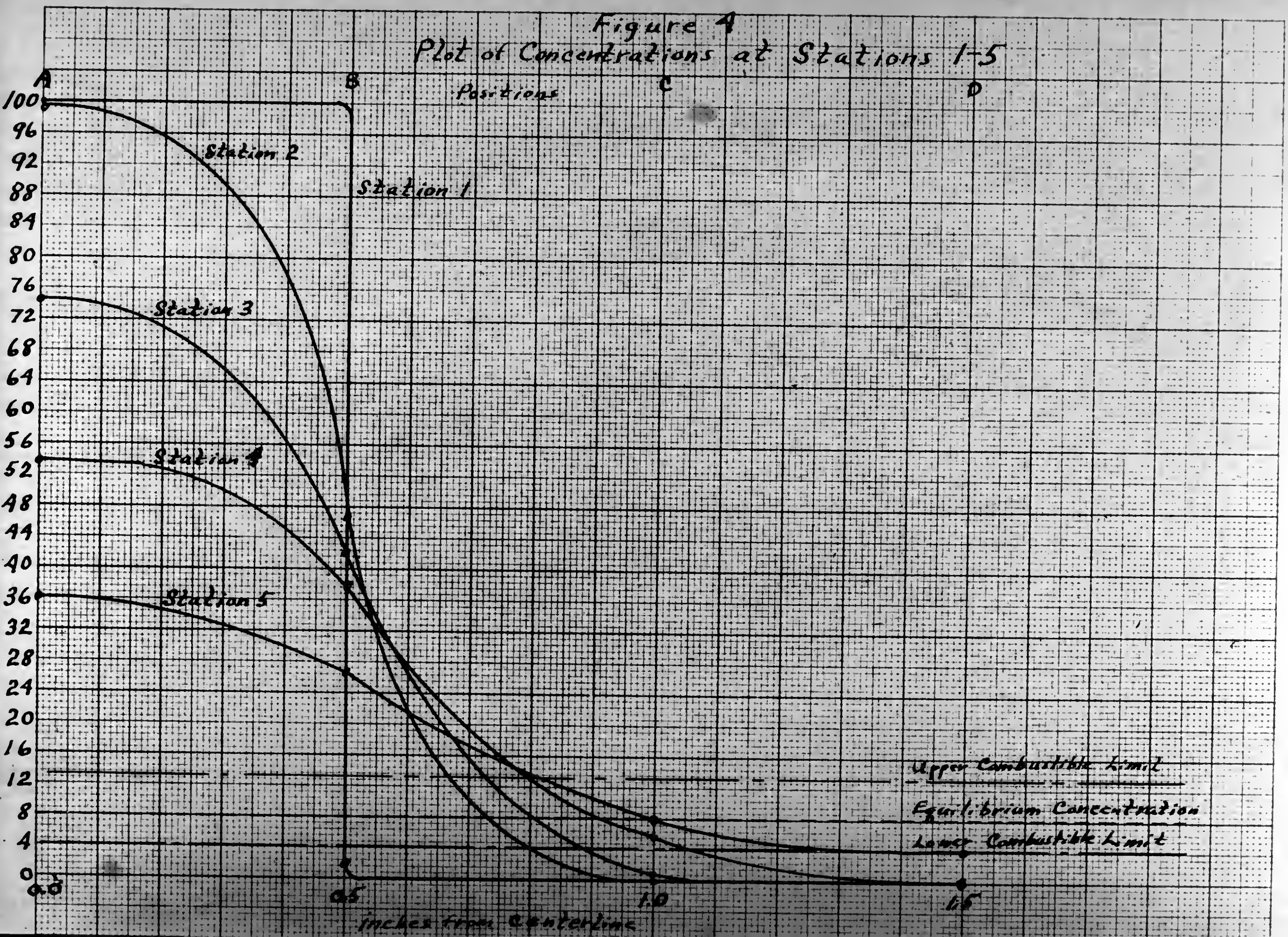

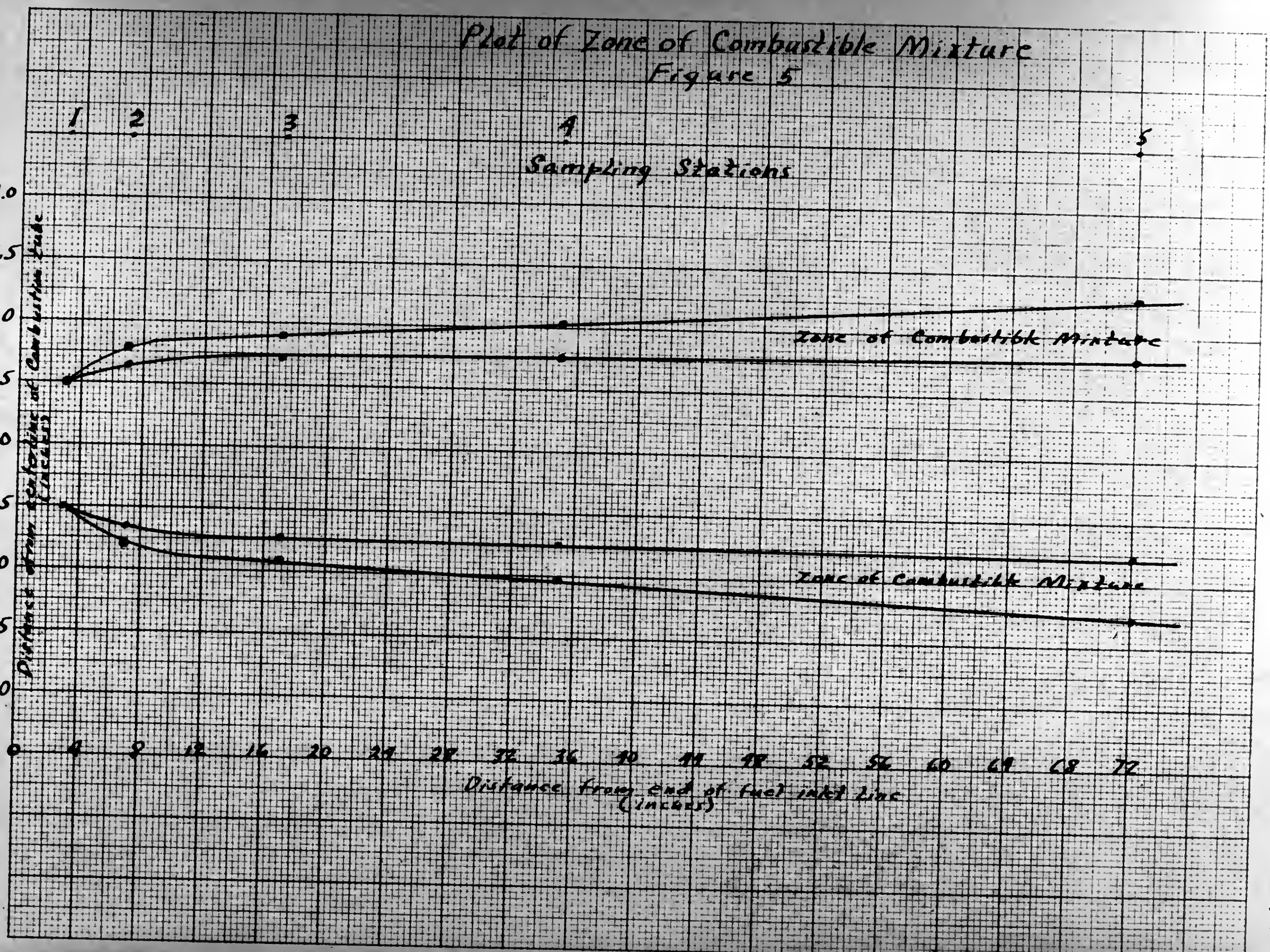
Plot of Zone of Combustible Mixture
Figure 5
1
2
3
4
5
Sampling Stations
2.0
1.5
1.0
0.5
0.0
0.5
1.0
1.5
2.0
Distance from centerline of Combustion tube (inches)
Zone of Combustible Mixture
Zone of Combustible Mixture
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
Distance from end of fuel inlet Line (inches)

APPENDIX

The data and calculation sheets included in the Appendix are divided into four sections. The material included in each section is outlined below:

Section 1, pages A - 2 through A - 4 includes the sample bulb weighing data.

Section 2, pages A - 5 and A - 6 includes the air and gas supply manometer readings and the sample position readings taken from the venier height measuring gauge.

Section 3, pages A - 7 and A - 8 includes the Pitot tube manometer readings and the sample temperature readings.

Section 4, pages A - 9 and A - 10 includes the calculations to obtain the values of the percent fuel gas in each sample from the data contained in Sections 1 and 3.

Section 1 - Data

2 May 1947 -

Bulb No.	4	5
Wt. of Bulb + Air	139.6804 gr.	165.7730 gr.
Wt. of Bulb	138.7941 gr.	165.1745 gr.
Wt. of Air	.8863 gr.	.5985 gr.

Ambient Temp. = 26.5° C Ambient Pressure = 746.0 mm.

Station I

Bulb # 5 - Tare - 165.1745 gr. Bulb # 4 - Sample - 165.1745 gr.
138.7941 gr.
26.3804 gr.

Position A		Position C	
Tare	26.3804 gr.	Tare	26.3804 gr.
	25.7230 gr.		25.5000 gr.
	.6574 gr.		.8804 gr.

Position B		Position D	
Tare	26.3804 gr.	Tare	26.3804 gr.
	25.5570 gr.		25.5005 gr.
	.8234 gr.		.8799 gr.

Station 2

Position A		Position C		
Tare	26.3804 gr.	Tare	26.3804 gr.	26.3804 gr.
	25.7200 gr.		25.4350 gr.	25.4840 gr.
	.6604 gr.		.9454 gr.	.8964 gr.

Section I

Position B			Position D		
Tare	26.3804	gr.	Tare	26.3804	gr.
	25.6050	gr.		25.5000	gr.
	.7754	gr.		.8804	gr.

Ambient Pressure 743.5 Station 3

Position A			Position C		
Tare	26.3804	gr.	Tare	26.3804	gr.
	25.6655	gr.		25.4995	gr.
	.7149	gr.		.8809	gr.
Position B			Position D		
Tare	26.3804	gr.	Tare	26.3804	gr.
	25.5940	gr.		25.4975	gr.
	.7864	gr.		.8829	gr.

Station 4

Position A			Position C		
Tare	26.3804	gr.	Tare	26.3804	gr.
	25.6150	gr.		25.5200	gr.
	.7654	gr.		.8604	gr.
Postion B			Position D		
Tare	26.3804	gr.	Tare	26.3804	gr.
	25.5485	gr.		25.4915	gr.
	.8319	gr.		.8859	gr.

Section I

Station 5

Position A

Tare	26.3804	gr.
	25.5680	gr.
	.8124	gr.

Position B

Tare	26.3804	gr.
	25.5485	gr.
	.8319	gr.

Position C

Tare	26.3804	gr.
	25.5045	gr.
	.8759	gr.

Position D

Tare	26.3804	gr.
	25.4915	gr.
	.8889	gr.

Section 2

Manometer Readings (Water)

Air Supply	Δ p = 17.8 cm. H_2O	Av. Temp. = 32.5° C
Gas Supply	Δ p = 7.5 cm.	Av. Temp. = 32.0° C
Air Boundary	Δ p = 9.75 cm.	
Gas Boundary	Δ p = 9.75 cm.	Height = 6.627"
Air Supply	Total pressure = 760.7 mm. Hg.	

Sampler Position Readings

Station 1		Station 3	
Top Reading	4.318"	Top Reading	4.335"
Plus Radius	1.910	Plus Radius	1.910
Position A	6.228"	Position A	6.245"
	.500		.500
Position B	6.728"	Position B	6.745"
	.500		.500
Position C	7.228"	Position C	7.245"
	.500		.500
Position D	7.728"	Position D	6.745"

Station 2		Station 4	
Top Reading	4.320"	Top Reading	4.320"
Plus Radius	1.910	Plus Radius	1.910
Position A	6.330"	Position A	6.230"
	.500		.500
Position B	6.730"	Position B	6.730"
	.500		.500
Position C	7.230"	Position C	7.230"
	.500		.500
Position D	7.730"	Position D	7.730"

Section 2

Station 5

Top Reading	4.320"
Plus Radius	1.910
Position A	6.230"
	.500
Position B	6.730"
	.500
Position C	7.230"
	.500
Position D	7.730"

Section 3

Pitot Tube Readings

				Total
Station 1				
Position A	= 12.4 cm. H_2O	= 9.1 mm. hg.	+ 746.0	= 755.1 mm. hg.
Position B	= 12.5 cm. H_2O	= 9.2 mm. hg.	+ 746.0	= 755.2 mm. hg.
Position C	= 12.6 cm. H_2O	= 9.3 mm. hg.	+ 746.0	= 755.3 mm. hg.
Position D	= 12.6 cm. H_2O	= 9.3 mm. hg.	+ 746.0	= 755.3 mm. hg.
Station 2				
Position A	= 12.5 cm. H_2O	= 9.2 mm. hg.	+ 746.0	= 755.2 mm. hg.
Position B	= 12.1 cm. H_2O	= 8.9 mm. hg.	+ 746.0	= 754.9 mm. hg.
Position C	= 11.0 cm. H_2O	= 8.1 mm. hg.	+ 746.0	= 754.1 mm. hg.
Position D	= 11.0 cm. H_2O	= 8.1 mm. hg.	+ 746.0	= 754.1 mm. hg.
Station 3				
Position A	= 10.3 cm. H_2O	= 7.6 mm. hg.	+ 743.5	= 751.1 mm. hg.
Position B	= 9.8 cm. H_2O	= 7.3 mm. hg.	+ 743.5	= 750.8 mm. hg.
Position C	= 10.1 cm. H_2O	= 7.5 mm. hg.	+ 743.5	= 751.0 mm. hg.
Position D	= 10.0 cm. H_2O	= 7.4 mm. hg.	+ 743.5	= 750.9 mm. hg.
Station 4				
Position A	= 10.2 cm. H_2O	= 7.5 mm. hg.	+ 743.5	= 751.0 mm. hg.
Position B	= 10.0 cm. H_2O	= 7.4 mm. hg.	+ 743.5	= 750.9 mm. hg.
Position C	= 10.2 cm. H_2O	= 7.5 mm. hg.	+ 743.5	= 751.0 mm. hg.
Position D	= 10.0 cm. H_2O	= 7.4 mm. hg.	+ 743.5	= 750.9 mm. hg.
Station 5				
Position A	= 10.4 cm. H_2O	= 7.7 mm. hg.	+ 743.5	= 751.2 mm. hg.
Position B	= 10.4 cm. H_2O	= 7.7 mm. hg.	+ 743.5	= 751.2 mm. hg.
Position C	= 10.3 cm. H_2O	= 7.6 mm. hg.	+ 743.5	= 751.1 mm. hg.
Position D	= 10.1 cm. H_2O	= 7.5 mm. hg.	+ 743.5	= 751.0 mm. hg.

Section 3

Sample Temperature Readings

Station 1

A 33°*C + 273 = 306°K

B 33° C + 273 = 306°K

C 33° C + 273 = 306°K

D 33° C + 273 = 306°K

Station 2

A 32.5*C + 273 = 305.5°K

B 32.5°C + 273 = 305.5°K

C 32.0°C + 273 = 305.0°K
25.0°C + 273 = 298.0°K

D 32.0°C + 273 = 305.0°K

Station 3

A 31.5°C + 273 = 304.5°K

B 31.0°C + 273 = 304.0°K

C 30.5°C + 273 = 303.5°K

D 30.0°C + 273 = 303.0°K

Station 4

A 29.0°C + 273 = 302.0°K

B 29.0°C + 273 = 302.0°K

C 28.5°C + 273 = 301.5°K

D 28.0°C + 273 = 301.0°K

Station 5

A 26.5°C + 273 = 299.5°K

B 27.0°C + 273 = 300.0°K

C 26.0°C + 273 = 299.0°K

D 25.0°C + 273 = 298.0°K

* Estimated

Section 4

Calculations

I. Correction of Density for Pressure and Temperature Changes:

Now:

$$d_1 = \frac{P_1T_2}{P_2T_1} \times d_2$$

and since the volume of sample was constant we may write:

$$W_1 = \frac{P_1T_2}{P_2T_1} \times W_2 \quad \text{where } W \text{ denotes weight.}$$

Let "W_2" be weight obtained from the sample weighings and "W_1" be the sample weights corrected to standard conditions.

$$\therefore \text{ Tare Air Sample wt.} = W_1 = \frac{P_1T_2}{P_2T_1} \times W_2$$

$$\therefore W_1 = \frac{760 \times 299.5}{746 \times 273} \times 0.8863 = 0.990 \text{ grs.}$$

Similarly we get:

Station 1

A = 0.742 gr.

B = 0.928 gr.

C = 0.992 gr.

D = 0.991 gr.

Station 2

A = 0.744 gr.

B = 0.874 gr.

C = 1.066 gr.
= 0.989 gr.

D = 0.991 gr.

Station 3

A = 0.806 gr.

B = 0.886 gr.

C = 0.990 gr.

D = 0.991 gr.

Station 4

A = 0.856 gr.

B = 0.896 gr.

C = 0.964 gr.

D = 0.989 gr.

Station 5

A = 0.901 gr.

B = 0.925 gr.

C = 0.971 gr.

D = 0.980 gr.

Section 4

II. Calculations of percent fuel gas in sample.

$$\% \text{ Fuel Gas} = \frac{0.991 - \text{wt. of sample}}{0.991 - 0.742} \times 100$$

Station 1

A = 100.0%

B = 2.5%

C = 0.0%

D = 0.0%

Station 2

A = 99.1%

B = 46.9%

C = 0.8%

D = 0.0%

Station 3

A = 74.3%

B = 42.2%

C = 0.4%

D = 0.0%

Station 4

A = 54.2%

B = 38.1%

C = 10.8%

D = 0.8%

Station 5

A = 36.1%

B = 26.5%

C = 8.0%

D = 4.4%

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M89 Mullane
An apparatus for the study of the turbulent diffusion flame.

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